DEVELOPMENT OF AN IMPROVED ALGORITHM OF MPPT TECHNIQUE FOR PHOTOVOLTAIC POWER GENERATION

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DEVELOPMENT OF AN IMPROVED ALGORITHM OF MPPT TECHNIQUE FOR PHOTOVOLTAIC POWER GENERATION

by

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LIST OF SYMBOLS

Symbols	Description
A	Constant with respect to temperature
B	Ideality factor of the junction
C	Capacitor
C_B	Battery capacity
C_{in}	Input capacitance
C_{iss}	Total input capacitance
C_{min}	Minimum capacitance
D	Duty Cycle
$D_{initial}$	Duty cycle initialization
D_m	Freewheeling diode
E	Energy
E_g	The band gap
f_s	Frequency switching
G	Irradiation
$I(k)$	PV module output current at k sampling
I_L	Inductor current
I_{mpp}	Current at maximum power point of PV
I_{ph}	Photocurrent source
I_{PV}	PV module current
I_s	Reverse saturation current
I_{sc}	Short circuit current
k	Boltzmann constant
k_T	Temperature coefficient
L	Inductor
L_{min}	Minimum inductance

n_p	Number of cells in parallel
n_s	Number of cells in series
P	Power
P_{in}	Input power
$P(k)$	PV module output power at k sampling
P_{loss}	Power losses
P_{mpp}	Power at maximum power point of PV
P_{out}	Output power
R	Resistor load
R_{pvm}	PV module internal resistance at maximum power
R_s	Series resistor
R_{sh}	Shunt resistor
S	Switch
t	Time
T	Temparature
T_a	Sampling time
t_d	Delay time
t_f	Fall time
t_r	Rise time
V_b	Battery voltage
V_C	Capacitor voltage
V_{gs}	Gate-source voltage
v_i	Input voltage correspond to input current
$V(k)$	PV module output voltage at k sampling
V_L	Inductor voltage
V_{mpp}	Voltage at maximum power point of PV
V_O	Output voltage

V_{oc}	Open circuit voltage
V_{PV}	PV module voltage
V_{ref}	Reference voltage
V_s	Supply voltage
v_{sense}	Sensing voltage
W_p	Peak Watt
ΔD	Duty cycle perturbation
η	Efficiency

LIST OF ABBREVIATION

	Description
A/D	Analogue to Digital
CCM	Continuous Conduction Mode
DC	Direct Current
DCM	Discontinuous Conduction Mode
DOD	Depth of Discharge
DSP	Digital Signal Processor
EPP	Estimate and Perturb and Perturb
ESR	Equivalent Series Resistance
HC	Hill Climbing
INC	Incremental Conductance
MPO	Modify Perturb and Observe
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
PCB	Printed Circuit Board
PGF	Panel Generation Factor
PI	Proportional and Integral
PIC	Peripheral Interface Controller
P&O	Perturb and Observe
PV	Photovoltaic
PWM	Pulse Width Modulation
SOC	State of Charge
STC	Standard Test Condition

PEMBANGUNAN TEKNIK ALGORITMA PTKM YANG DITAMBAH BAIK BAGI PENJANAAN KUASA FOTO-VOLTIK

ABSTRAK

Tesis ini membentangkan teknik kawalan mudah yang telah digunakan dalam pengesan titik kuasa maximum (PTKM). Sebuah algoritma baru untuk pengecasan bateri, perlindungan pengecasan berlebihan dan teknik pengesanan kuasa maximum dalam pengusikan dan pemerhatian (P&P) telah dilaksanakan. Peningkatan teknik kawalan telah mencapai kecekapan yang optimum bagi sistem FV yang berdiri sendiri. Pengunaan P&P yang lebih baik dalam penukar AT-AT buck segerak untuk penggunaan bateri caj telah mengoptimumkan kuasa maximum tersedia untuk modul FV. Reka bentuk penukar AT-AT buck segerak telah mencapai 80% kecekapan. Didapati bahawa dengan algoritma G&L PTKM yang ditambah baik telah menunjukkan peningkatan keluaran kuasa FV sebanyak 13%, jika dibandingkan dengan sistem FV tanpa implimentasi PTKM.

DEVELOPMENT OF AN IMPROVED ALGORITHM OF MPPT TECHNIQUE FOR PHOTOVOLTAIC POWER GENERATION

ABSTRACT

This thesis presents a simple control technique which was used in Maximum Power Point Tracking (MPPT). A new algorithm for battery charging, overcharge protection and maximum power tracking in Perturbation and Observation (P&O) technique was implemented. The improvement of the control technique had achieved an optimal efficiency for the stand-alone PV system. The application of improved P&O in synchronous DC-DC buck converter for battery charging application had optimize the maximum available power for PV module. The synchronous DC-DC buck design achieved 80% efficiency. It is found that with an improved P&O MPPT algorithm had increased maximum PV output power by 13% when compared to a PV system without MPPT implementation.

CHAPTER 1
INTRODUCTION

1.1 Research Motivation

The demand for commercial energy is projected to continue its upward trend as both the world population and the living standard increase (Nezhad, 2009). The increase in consumption is mainly driven by the expansion of industrialization. Meeting the global demand for energy is now the key challenge to sustained industrialization (Liserre et al., 2010). The exploitation of fossil fuels during centuries and an extraction of energy from nuclear processes raise environmental issue, safety and political problems.

On the other hand, it is recognized and acknowledged that renewable and non-conventional forms of energy will play crucial role in the future as they are environmentally friendly, easy to use, clean energy and are bound to become economically more feasible with increased use (Kothari, 2000). Renewable energy term is derived from a broad range of resources, all of which are based on self-renewing energy sources such as sunlight, flowing water, wind, the earth’s internal heat and biomass comprise energy crops, agricultural and industrial waste, and municipal waste (Bull, 2001).

Solar energy specifically a photovoltaic (PV) is the most exploited renewable energy sources alongside with hydroelectric and wind power. Over the years, renewable energies have gone through one of the biggest growths in percentage, being comparable to the development of coal and lignite energy but still below that of natural gas. In 2007, the world’s renewable energy production share has been estimated as 19%. However, 16% are attributable to hydroelectric energy production and hence, PV energy production is still very modest. Despite the silicon inadequacy in recent years, the PV industry is growing at more than 30% annually and the cost of PV energy will reach the break-even point very soon in many countries. As of 2009, it is evident that wind energy is becoming well established with 1% of world energy production while solar energy is going through an impressive growth. In Asia and Australia, renewable energies are growing but the share within overall energy production is very divergent from country to country. The policies of Asian and Pacific countries with 35% of energy's share will perharps be more significant in the future energy scenario. Indeed, developing countries like China and India continuously require more energy where China's energy's share has increased 1% every year since 2000 (Liserre et al., 2010).

A PV module is fabricated from a number of cells connected together, which are further interconnected in a series-parallel configuration to form PV arrays. The modules fall into several categories including mono-crystalline, poly-crystalline and thin-film. The capital cost of photovoltaic panels has fallen from more than $ 50/W in the early 1980s to about $ 5/W today. Eventhough this is still higher than the price of conventional base load electricity, commercial markets are booming in developing countries for remote telecommunication, remote lighting and signs, remote home and others. Investment in renewable energy resources will in the long run balance the national energy production, guarantee energy security and encourage sustainable progress (Akuru and Okoro, 2010). PV offers many advantages for instance incurring no fuel costs, not being polluted, requiring little maintenances and others. When developing a PV generation system, reliability becomes a major issue in dealing with. PV unit sizing, types and combinations of sources, energy storage technologies, control procedures and the system internal connections are the typical considerations of reliability (Tucker and Negnevitsky, 2011).

Efficiency is another important aspect need to consider when developing a system that is based on renewable energy resources. By improving the efficiency of the systems, it will eventually improve system’s reliability. PV modules still have relatively low conversion efficiency and therefore scheming maximum power point (MPP) is crucial in a PV power generation system. The PV module has a nonlinear current-voltage and power-voltage characteristics varying with irradiance and temperature that significantly affect the module power output. At the maximum power point (MPP) of I-V and P-V characteristic curves, the PV operates at its highest efficiency. Therefore, many procedures have been developed to determine MPP. MPPT stands for maximum power point tracking is a power control technique which able to find MPP and extract the maximum power available on PV module and deliver to the load through DC-DC converter. According to the development history of techniques, MPPT can be classified in two categories which are conventional techniques and artificial intelligent techniques (Khaehintung et al., 2006). The most significant conventional techniques are Hill Climbing (HC), Perturbation and Observation (P&O), Incremental Conductance (INC), Fractional Open-Circuit Voltage and Short-Circuit Current. The most applicable artificial intelligence techniques are Fuzzy Logic and Neural Network methodologies. (Esram and Chapman, 2007) states that the methods mentioned vary in complexity, sensor required, convergence speed, cost, implementation hardware and other aspects. Among them, P&O method has been attracted much attention due its simplicity. The design and control methods to harvest maximum power available from PV module using P&O technique will be investigated in this research.

1.2 Problem Statement

Until now, a number of MPPT techniques have been developed for PV systems and from all conventional MPPT techniques, they maximize the power output from modules for a given set of conditions by searching the best working point of the power curve characteristic and then controls the current through the modules or the voltage across them. The fundamental benefit of MPPT is that is can convert extra PV module voltage into additional charging current if charging application is used. If there is lots of excess voltage, lots of extra current and several hours of charging could be saved. However, there are two existing drawbacks encountered while generating power from PV modules. The first one is that, the efficiency of PV module is very low especially under low irradiation states and the second drawback is the amount of output power generated by PV module is affected by weather conditions namely irradiation and temperature. The changing irradiance or temperature alters the shape of a hill that often leads the climbing scheme to wrong directions in which eventually affect the reliability and overall performance of the PV power generation system.

1.3 Research Objective

The primary objective of this research is to develop a new maximum power point tracking (MPPT) technique for photovoltaic power generation. To achieve the main objective, the sub objectives are listed below:

1. To develop a stand-alone photovoltaic (PV) system with maximum power point tracking (MPPT) technique for power generation
2. To optimize the maximum power available on PV module by deploying an improved P&O MPPT control technique with DC-DC power converters.

1.4 Research Approach

Firstly, the potential of renewable energy in Nibong Tebal is analyzed in order to estimate the available energy that can be produced by the PV system. Davis Instruments' Health Weather-Link is employed in order to store, view and plot the weather data gathered by the station which placed near the PV module. The pattern, mean, maximum and range of the solar irradiation and temperature had been studied that would give an overview characteristic of solar energy potential in Nibong Tebal. This information can be further used for sizing a PV system in correspond to the availability of solar energy potential in Nibong Tebal. Then, the DC-DC buck converter is developed to provide robust and high performance power point tracker acting as an intermediate between supply source and load. Lastly, a MPPT algorithm control method that is capable of tracking the MPP under variable changing of environmental condition is develop. After having the design and working idea of development a maximum power point tracking (MPPT) technique for PV power generation, a simulation is carried out to verify the idea and the performance of the proposed P&O MPPT algorithm by using Matlab-Simulink software. Besides having the simulation, a hardware prototype of the proposed model is built to validate the performance in the real case scenarios.

The scope of the research work generally covers three major components. The first part of the study is sizing of PV systems in Nibong Tebal, Penang. In this part, it will focus on the investigation and evaluation of the solar energy potential in Nibong Tebal by studying the solar irradiation and temperature data from the meteorological weather station at USM, Nibong Tebal. The second components that will be studied in this research work are building the Matlab-Simulink model of PV system with MPPT technique and performing the simulation according to the PV module reference model. The Matlab-Simulink model is used to verify the MPPT control strategy in order to maximize the generated output power from the PV power generation system based on the proposed control method. The final parts of the research work are to develop hardware system of an improved perturbation and observation (P&O) maximum power point tracking (MPPT) technique for stand-alone PV power generation in Nibong Tebal.

1.5 Thesis Outline

The thesis is divided into five main chapters which are the introduction, literature review, methodology, results, discussion as well as conclusions and recommendations. The outlines of the remaining four chapters are as follows

Chapter 2 will explain in details the literature review of renewable energy, solar energy and present the MPPT control that currently exist for a PV system. It also would provide an in-depth derivation of the formula as well as the theories in every single component which include PV characteristic, DC-DC buck converter, and the MPPT control strategy. The operation of DC-DC buck converter in continuous conduction mode (CCM) will be devoted. In addition, the literature survey on the work of previous researchers will be carried out. The three most used MPPT techniques are discussed. In the end, a short summary regarding MPPT control technique will be discussed in concluding remarks section at the end of this chapter.

In Chapter 3 will elaborate in details the framework of the research, started with the study the potential of solar energy and PV sizing system in Nibong Tebal. Later, the design of digital MPPT controller is discussed and follows by scheming synchronous DC-DC buck converter. Then, an improved P&O algorithm is presented and a computer simulation is carried out in Matlab-Simulink. The hardware implementation of stand-alone PV system with MPPT technique and the evaluation of performance for the whole system is presented at the end of the chapter.

In Chapter 4, it clarifies about the analysis of simulation and experimental results as well as a stand-alone PV system with MPPT for power generation. Data are tabulated in tables and graphs are presented in a way that the significance of certain variables can be visualized better. Figures and diagrams are presented in great detail in order to aid in understanding the whole research and its benefits.

Finally, Chapter 5 will conclude this thesis. It provides a conclusion of achieving objectives set earlier in the thesis. The concluding remark together with summarized discussion, addressing issues and limitations will be justified. The recommendation for future work will also be stated in this chapter.

1.6 Research Contributions

The contributions of this research are summarized below:

1. The method of sizing a PV system with the availability of solar radiation at selected sites has been produced.

2. The step by step procedure for modeling the PV module has been presented. The detailed modeling procedure will be able to give readers a detailed insight on photovoltaic research, particularly in the area of I-V and P-V characteristics of a PV module.

3. The proposed complete system has incorporated all the sub-systems which consists of current sensor circuit, voltage regulator, MOSFET drivers, bootstrap circuit and microcontroller block on a single working board for small scale stand-alone PV system and can be used as a reference model for future research in the photovoltaic field.

4. An improved perturbation and observation (P&O) MPPT algorithm with a charging battery scheme that could optimized PV output power is proposed and verified.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This chapter provides an overview of the literature pertaining to the proposed research project specifically on currently exist MPPT control strategy for a PV system. The literature review is started with the preface on the topic of renewable energy, solar energy, principle operation of PV and DC-DC converter topology. Subsequently, scholarly materials regarding MPPT control control strategy has been read, analyze and evaluate. Last section, Section 2.8 will discuss the concluding remarks of the Chapter 2.

2.2 Renewable Energy

Renewable energy system not produces any waste or pollutants that contribute to acid rain, health problem and do not involve environmental cleanup costs or waste disposal fees. A potential global climate change caused by excess carbon dioxide and other gases in the atmosphere is the latest environmental concern for the green non-government organization. For instance, world climate change is debated seriously in (Hammons et al., 2000). A power generation system using solar, wind and geothermal sources does not contribute any carbon dioxide to the atmosphere. In fact, today renewable sources of electricity help the United States avoid about 70 million metric tons of carbon emissions per year that would have been produced had that electricity being generated by fossil fuels.

Although the energy of the sun and wind has been utilize by mankind for millennia, modern applications of renewable energy technologies have been under serious development for only about 20 years (Bull, 2001). One of the most promising markets for renewable enery exist in supplying electricity to remote areas, especially in developing countries. Solar energy and wind power are not in high density and are available on an intermittent or irregular fashion. Renewable energy is not load-following. The utilization of energy and power in the industry, living, and working places may often be in different phase compared to the period of availability of renewable energy (Peiwen, 2008).

2.3 Solar Energy

Photovoltaic (PV) is the most exploited renewable energy sources along with hydroelectric and wind power (Liserre et al., 2010). Photovoltaic device uses semiconductor materials such as silicon to convert sunlight to electricity. They contain no moving parts and generate no emissions while in operation. Photovoltaic devices can be used in small cells, modules, arrays and extremely modular. Photovoltaic systems require few servicing or maintenance and has typical lifetimes of about 20 years. PV modules are rated in terms of their peak output (peak Watt or W_p), which is the maximum power that they will produce given optimum solar input and operating conditions. The average power produced will be closer to the rated peak output in locations where there is a high level of incidence radiation during the year. The output of a PV module varies depending on the amount of incident light and other factors such as temperature and the cleanliness of the cell surfaces (Mestre and Diehl, 2005). PV generation efficiency and power quality are the fundamental issues. PV power systems are usually integrated with control algorithms that have the function of ensuring maximum power point operation.

Output power of PV module is maximized only at a certain voltage level of 17V. This point, which is named maximum power point (MPP) is affected by solar irradiation and environmental temperature, so it is required some techniques in order to track the MPP. These techniques are generally called MPPT which is stand for maximum power point tracking. MPPTs utilize a power converter in series or parallel to extract maximum available energy from PV cells or modules and deliver it to the load.

2.4 Principle Operation of Photovoltaic (PV)

Photovoltaic (PV) generation exhibits numerous merits such as cleanness, low maintenance, no noise and regarded as one of the most essential renewable energy sources. A PV cell is basically a semiconductor diode whose *p-n* junction is exposed to light (Villalva et al., 2009). As sunlight strikes a solar cell, photons with energy greater than the corresponding energy of the band-gap are absorbed, causing the emergence of pair's electron-hole from a low energy states to an unoccupied higher energy level. These carriers are separated under the influence of electric fields within the junction and hence the *p-n* junction is electrically shorted creating a current flow that is proportional to the incidence of solar irradiation and temperature.

PV cells are combined in series and parallel connection to form larger units called PV modules, which are further interconnected in a series-parallel configuration to from PV arrays (Gow and Manning, 1996). PV cells can be classified into several types like as amorphous solar cell, mono-crystalline, polycrystalline solar cell and etc.

The irradiation level and temperature are the focal factors for characteristic of solar cell. Even though the solar cell panels were made with same manufacture technology, it still shows different I-V characteristics along variation of circumstance of solar irradiation and cell temperature (Jae-Hyun et al., 2001).

Generally, the equivalent circuit of a solar cell is represented by a single-diode model (Phang et al., 1984). The single-diode model composes of four components namely a photocurrent source I_{ph}, a diode parallel to the sources, a series resistor, R_s and a shunt resistor, R_{sh} as displayed in Figure 2.1.

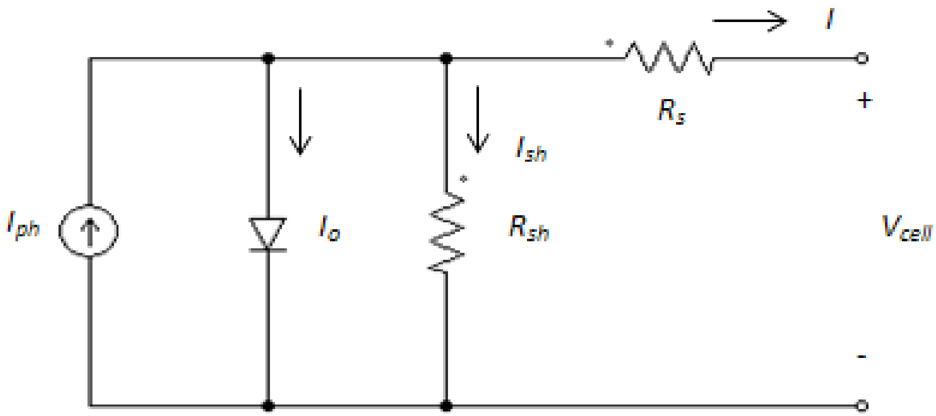

Figure 2.1: PV cell modeled as diode circuit.

The series resistance, R_s is the internal resistance of the cell and it depends on the resistance of the semiconductor. The shunt resistance, R_{sh} is due to leakage at the junction. The I-V characteristic of a PV cell is governed by the following equations:

$$I = I_{ph} - I_o - I_{sh} \tag{2.1}$$

$$I = I_{ph} - I_s \left[exp\left(\frac{q(V_{cell} + R_s I)}{BkT} \right) - 1 \right] - \frac{V_{cell} + R_s I}{R_{sh}} \tag{2.2}$$

where I_{ph} is the light current, I_s as reverse saturation current of the diode, k *is* Boltzmann constant 1.38x10-19, B is ideality factor of the junction, V_{cell} is voltage of PV cell and T is temperature in Kelvin. The light current, I_{ph} depends on temperature and irradiation while the reverse saturation current of the diode, I_s depends only on the temperature. Relationship between I_{ph} and I_s with irradiation, G and temperature, T is governs in Equation (2.3) and Equation (2.4) respectively.

$$I_{ph} \quad = \frac{G}{1000}\left(I_{sc} + k_T(T - 298)\right) \tag{2.3}$$

and

$$I_s = AT^3 exp\left(\frac{-qE_g}{BkT}\right) \tag{2.4}$$

where G, I_{sc}, $k_{T,}$ $E_{g\,,}$ A represent individually the irradiation, short-circuit current of the PV cell, the temperature coefficient, the band gap and constant with respect to temperature (Rosell and Ibáñez, 2006).

The PV cells are the basic components of all PV system. They can be connected in series to increase their operating voltage and in parallel to increase their current capacity. The total current in the PV module can be calculated as follows:

$$I = n_p I_{ph} - n_p I_s \left[exp\left(\frac{q(V_{cell} + R_s I)}{n_s BkT}\frac{n_s}{n_p}\right) - 1\right] - \frac{V_{cell}\dfrac{n_p}{n_s} + R_s I}{R_{sh}} \tag{2.5}$$

where n_s are the number of cells in series and n_p are the number of cells in parallel.

In this research, the BP275F solar module is taken as the reference model for simulation and the technical specification details are given in Table 2.1 under standard test conditions (STCs) which means an irradiation of 1000W/m^2 with an AM 1.6 spectrum at 25^{o}C.

Table 2.1: Technical specification data of BP275F 75W module

Description	Rating
Rated power, P	75.00 W
Voltage at maximum power (V_{mp})	17.00 V
Current at maximum power (I_{mp})	4.45 A
Open circuit voltage (V_{oc})	21.4 V
Short circuit current (I_{sc})	4.75 A
Total number of cells in series (n_s)	36
Total number of cells in parallel (n_p)	1

2.5 DC-DC Buck Converter

A number of modules can be arranged together either in parallel or in series to form a PV array. The amount of PV output voltage depends on the arrangement of modules. A BP 275F PV module can reach out 75 W and the value of its open circuit voltage is 21.4 V. Due to the load specification and the need to provide a lower voltage with high efficiency, a regulator or converter is required in most PV applications in order to step-down the output voltage that they generate. In addition, PV modules require an intermediate power point tracker as their I-V characteristics are nonlinear (Veerachary, 2011). The proposed topology in this research is DC-DC buck converter which has the voltage output lower than the input source. The PV system is later simulated using Matlab-Simulink software.

As mentioned before, the average output voltage, V_o is less than the input voltage, V_s in a DC-DC buck converter, hence the name 'Buck', a very popular DC regulator for PV application. The typical circuit diagram of a DC-DC buck converter is illustrated in Figure 2.2.

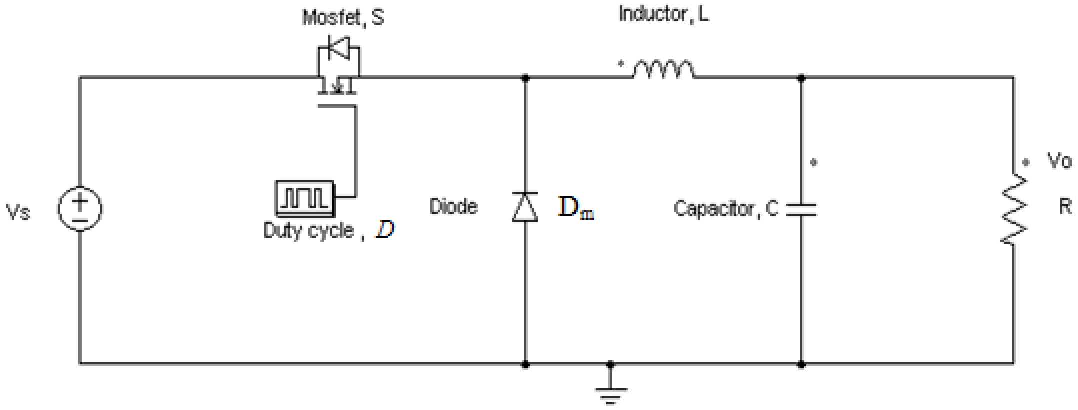

Figure 2.2: Circuit diagram of a DC-DC buck converter.

2.5.1 Principle of Operation

A DC-DC buck converter consists of two operating modes which are continuous conduction mode (CCM) and discontinuous conduction mode (DCM). Usually CCM technique is applied for efficient power conversion while the DCM is suitable for a lower power and stand-by application (Khader, 2011).

For the CCM, the inductor current never reaches zero during one switching cycle as illustrated in Figure 2.3. It has a smooth input current because an inductor is connected in series with the power source (Erickson, 2005).

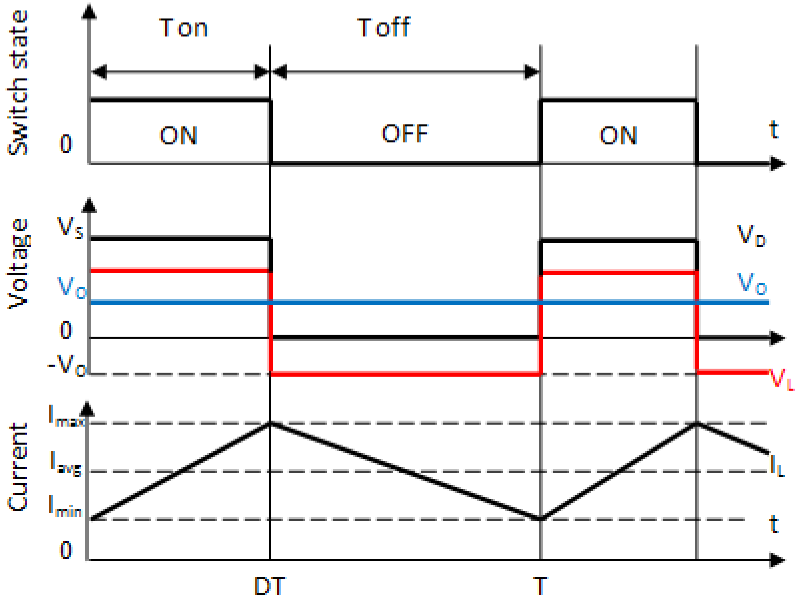

Figure 2.3: Waveform of voltage and current.

Duty cycle, D is defined as the ratio of the duration of the event to the total period of the signal and it is given by

$$D = \frac{T_{on}}{\mathrm{T}} \tag{2.6}$$

Where T_{on} is the duration that the function is active and T is the period of the function. The value of duty cycle, D can be varied from 0 to 1. The operation of the DC-DC buck circuit can be separated into two modes wherein for mode 1**,** switch, S is *ON* and mode 2 wherein switch, S is *OFF*.

1) *Mode 1: Switch, S is ON*

The equivalent circuit for mode 1 when Switch, *S* is *ON* (during time interval, T_{on}) and the waveforms of voltages and currents are shown in Figure 2.4 and Figure 2.5 respectively.

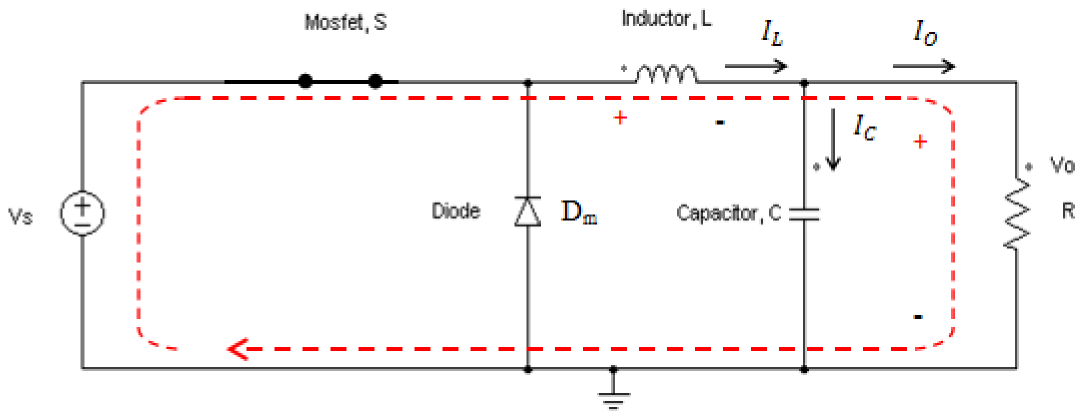

Figure 2.4: Equivalent circuit when switch, S in *ON* mode.

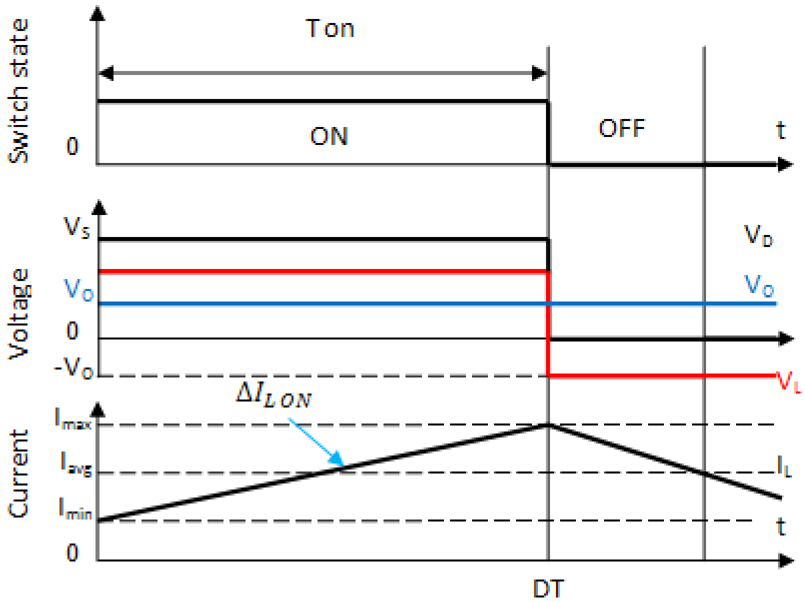

Figure 2.5: Waveform of voltage and current when switch, S in *ON* mode.

When switch, *S* is *ON*, the input current, I_L flows through the inductor, *L* filter capacitor, *C* and load resistor, *R*. By applying the Kirchhoff's voltage law, the inductor voltage, V_L is given by:

$$V_L = V_s - V_o \tag{2.7}$$

and

$$L\frac{di_{ON}}{dt} = V_s - V_o \tag{2.8}$$

Integrating i with respect to dt leads to;

$$\Delta I_{L\ ON} = \left(\frac{V_s - V_o}{L}\right)DT \tag{2.9}$$

where V_s , V_o, D and $\Delta I_{L\ ON}$ are supply source, output voltage, duty cycle and value of inductor current, I_L during the *ON* state respectively.

2) *Mode 2: Switch S is OFF*

The equivalent circuit for mode 2 when Switch, *S* is *OFF* and the waveforms of voltages and currents are shown in Figure 2.6 and Figure 2.7 respectively.

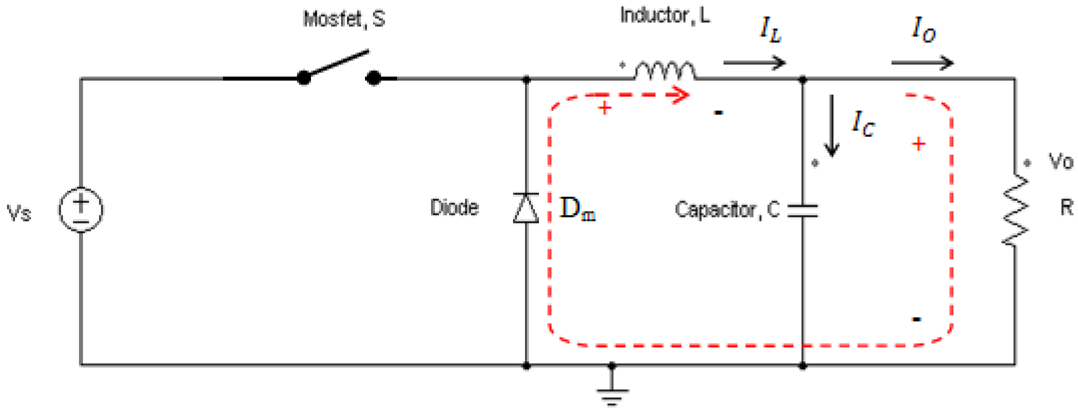

Figure 2.6: Equivalent circuit when switch, *S* in *OFF* mode.

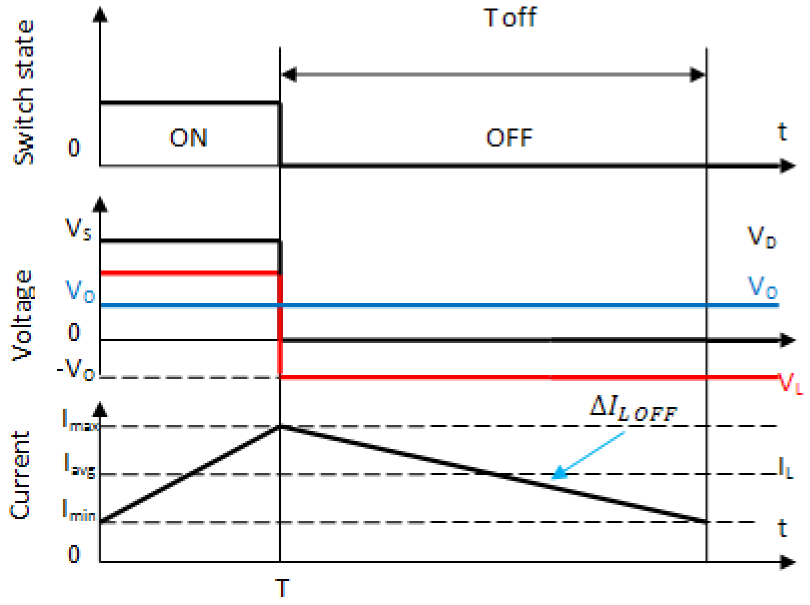

Figure 2.7: Waveform of voltage and current when switch, *S* in *OFF* mode.

When switch, S is OFF the freewheeling diode, D_m gets conducted (short circuited) due to the energy stored in the inductor and the inductor current continues to flow through L, C, R, and diode D_m. Therefore:

$$V_L = -V_c = -V_o \tag{2.10}$$

And

$$-V_o = L\frac{di_{OFF}}{dt} \tag{2.11}$$

Integrating i with respect to dt leads to;

$$\Delta I_{L\,OFF} = \left(\frac{-V_O}{L}\right)(1 - D)T \tag{2.12}$$

where V_c is the value of voltage across the capacitor, C and $\Delta I_{L\,OFF}$ is the value of inductor current, I_L during OFF state.

3) Steady State Operation

During the steady state operation,

$$\Delta I_{L\,ON} + \Delta I_{L\,OFF} = 0 \tag{2.13}$$

And

$$\left(\frac{V_S - V_O}{L}\right) DT + \left(\frac{-V_O}{L}\right)(1 - D)T = 0 \tag{2.14}$$

Therefore, by solving Equation (3.14) gives the output voltage, V_o as

$$V_O = DV_s \qquad ; 0 < D < 1 \tag{2.15}$$

4) Continous Inductor Current and Capacitor Voltage

For the system to conduct current in continuous conduction mode (CCM), the minimum inductor current, I_L must be higher or equal to zero.

$$I_{min} \geq 0 \tag{2.16}$$

From (Rashid, 2004), the minimum inductance, L_{min} and capacitance, C_{min} is given by:

$$L_{min} = \frac{(1 - D)R}{2f_s} \tag{2.17}$$

And

$$C_{min} = \frac{1 - D}{16L{f_s}^2} \tag{2.18}$$

where f_s is frequency switching of the MOSFET which is the reciprocal of the switching period, *T*. In practice, the calculated minimum value for input and output capacitor may be inadequate because output ripple voltage specifications restrain the amount of allowable output capacitor equivalent series resistance or ESR.

Attaining a sufficiently low value of ESR often requires the use of a much larger capacitor value than calculated. Taking into account that the ripple of the PV output current should be less than 2% of its mean value (Theocharis et al., 2005), and then the input capacitor value is calculated to be

$$C_{in} \geq \frac{(1-D)(I_{om}\,D_{max})}{0.02 \times I_{pvm}\,R_{pvm}\,f_s} \tag{2.19}$$

where I_{pvm} is the converter input current at maximum input power, D_{max} duty cycle during maximum output power, while R_{pvm} and V_{inm} are the PV module internal resistance and the PV module output voltage at the maximum power point respectively and is defined as

$$R_{pvm} = \frac{V_{inm}}{I_{pvm}} \tag{2.20}$$

The imperative simulation parameters are listed in Table 2.2. These parameters will be used later in designing hardware of DC-DC buck converter.

Table 2.2: DC-DC buck converter calculated parameters

Components	**Value**
Mosfet Switch, *S*	IRF540N
Inductor, *L*	50 uH
Diode, D_m	MUR 860
Output Capacitor, *C*	220 uF
Load, *R*	4 Ω
Frequency switching, f_s	20 kHz
Input Capacitor, C_{in}	220 uF

2.6 Principle Operation of Maximum Power Point Tracking, MPPT

Maximum power point tracking is a power control technique that operates the PV modules in a manner that allows the modules to produce all the power they are capable of. To get a better understanding how MPPT works, let's examine a graph of PV array battery charging power transfer as illustrate in Figure 2.8 (Woodbank, 2005).

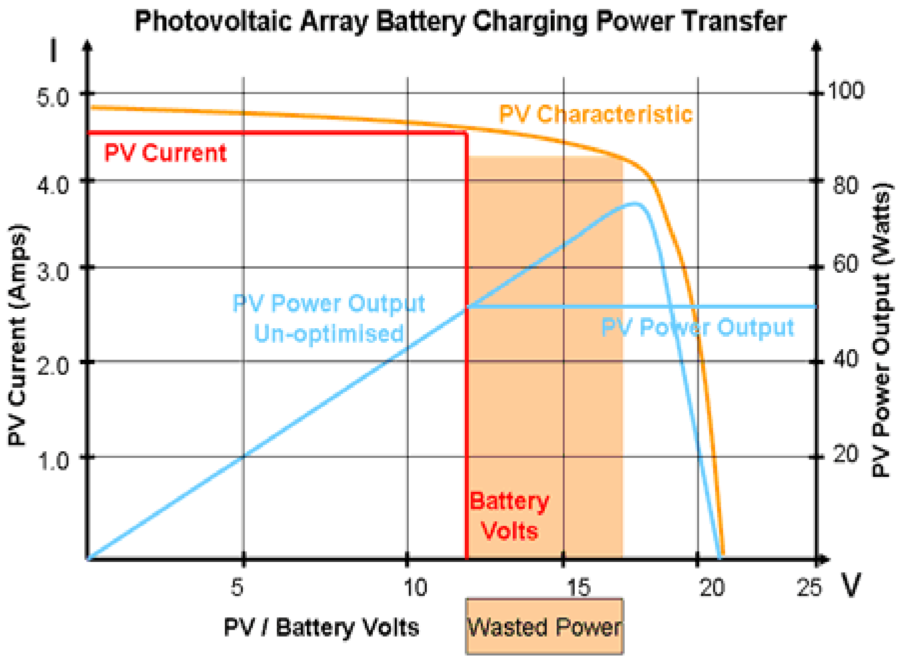

Figure 2.8: Graph of PV array battery charging power transfer.

When a conventional PV module connects directly to the battery, it will force the module to operate at battery's voltage of 12V which is not an ideal operating voltage of 17V for the available maximum power that module can generate. Therefore there is a portion of power that could not be exact from the module and it is a wasted power. The used of MPPT will vary the electrical operating point of the PV module so that the module is able to deliver the maximum available power it has.

2.7 Photovoltaic Control Strategy

In order to extract maximum power that PV module could harvest, researchers have come out with numbers of the control strategy. The methods vary in complexity, cost, sensor required, convergence speed, implementation hardware and other aspects. However, according to the development history of techniques, they can be classified in two categories namely conventional techniques and artificial intelligent techniques (Khaehintung et al., 2006). The most significant conventional techniques are Hill Climbing (HC), Perturbation and Observation (P&O), Incremental Conductance (INC), Fractional Open-Circuit Voltage and Short-Circuit Current. The most applicable artificial intelligence techniques are Fuzzy Logic and Neural Network methodologies. The characteristic power-voltage (P-V) curve for a PV array is shown in Figure 2.9.

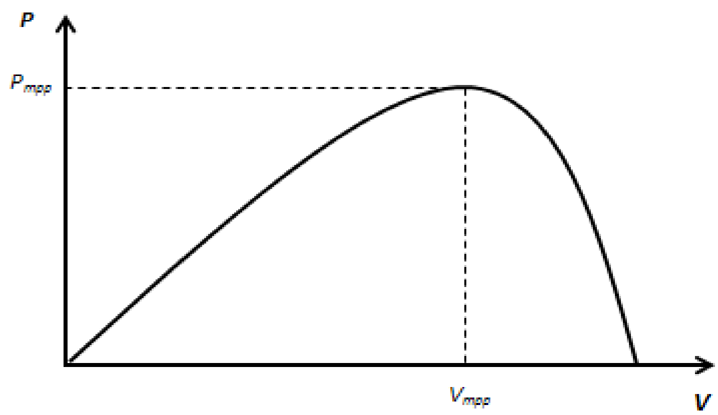

Figure 2.9: Power - Voltage curve for a PV module.

The problem raised by MPPT techniques is to automatically find the voltage V_{mpp} at which a PV module should operate to attain the maximum power output P_{mpp} under a given temperature and irradiance (Esram and Chapman, 2007). Several techniques as mentioned previously are discussed in details in an arbitrary order.

2.7.1 Hill Climbing (HC)

Hill climbing (HC) is a popular MPPT technique ever develops due to its simplicity and easy to implement. A classical HC technique as illustrate in Figure 2.10 and Figure 2.11 operated with a fixed voltage size which controls the sign of P-V curve's slope each calculation step and makes the appropriate voltage alteration.

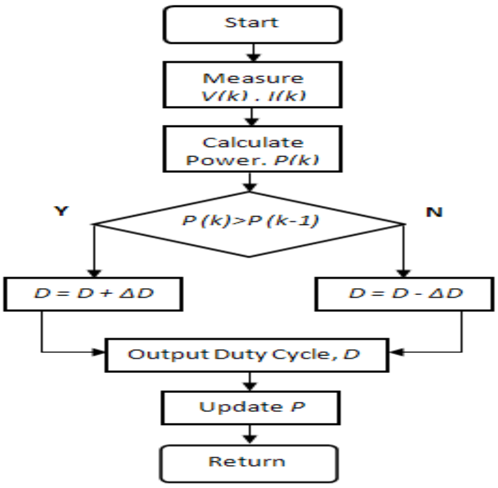

Figure 2.10: Flow diagram of HC.

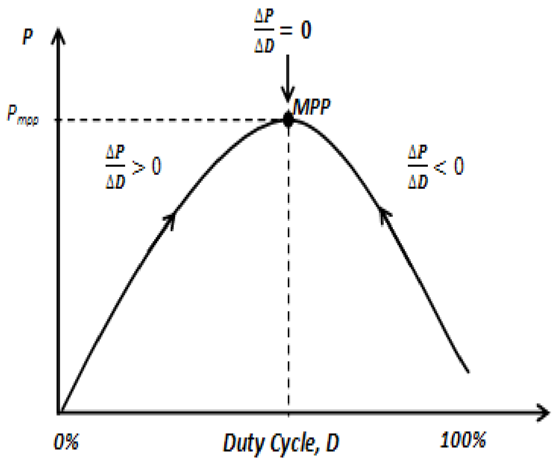

Figure 2.11: Power-Duty curve of the HC.

HC have been discussed in (Yu et al., 2002). The duty cycle, D in every sampling period is determined by the comparison of the power at the present time and previous time. If the incremental power $\Delta P > 0$, then the duty cycle should be increased in turn to make $\Delta D > 0$. Then if $\Delta P < 0$,, the duty cycle is reduced to make $\Delta D < 0$.

Shortcomings of the HC method are described below. Figure 2.11 is the Power-Duty (P-D) curve diagram of PV modules when the power interface device is DC-DC buck converter. If the initial operating point of the PV system is located on the left side of the MPP, the duty cycle has to be continuously increased on the basis of the judgment procedure of the HC method in order to track the maximum power point.